

Yet Another Model of Soft Gamma Repeaters

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Abstract

We develop a model of SGR in which a supernova leaves planets orbiting a neutron star in intersecting eccentric orbits. These planets will collide in $\sim 10^4$ years if their orbits are coplanar. Some fragments of debris lose their angular momentum in the collision and fall onto the neutron star, producing a SGR. The initial accretion of matter left by the collision with essentially no angular momentum may produce a superburst like that of March 5, 1979, while debris fragments which later lose their angular momentum produce an irregular pattern of smaller bursts.

Subject headings: Accretion—Gamma-rays: Bursts—Stars: Neutron

1. Introduction

More than a hundred models of gamma-ray bursts (GRB), including soft gamma repeaters (SGR), have been published (Nemiroff 1994), yet there is at present no satisfactory and generally accepted model of SGR. The distinction between “classical” GRB and SGR was not recognized until 1987 (Atteia, *et al.* 1987; Laros, *et al.* 1987; Kouveliotou, *et al.* 1987), so that theorists usually attempted to explain both classes of events with a single model. However, most of the basic facts about SGR were appreciated immediately following the observation of the superburst of March 5, 1979 (Cline 1980) from SGR 0526-66 in the LMC; specifically, their distance scale, association with young supernova remnants, repetition and likely origin in slowly rotating neutron stars were apparent. Reported annihilation spectral features were used to infer (Katz 1982) an upper bound to the magnetic field of $\approx 10^{13}$ gauss, although recent controversies regarding the reality of spectral features from “classical” GRB and the unclear spectrum of March 5, 1979 itself suggest that the features and the bound on the field may be questionable (Duncan and Thompson [1992] discuss models with much larger field). More recently, a distance scale of ~ 10 Kpc for the two non-LMC SGR (SGR 1826-20 and SGR 1900+14) and other evidence were reviewed by Norris, *et al.* (1991), and at least two of the three SGR are now known to be associated with young SNR (Kulkarni and Frail 1993; Kouveliotou, *et al.* 1994).

Two classes of models extensively discussed for GRB have appealing features as explanations of SGR, but fail at least one crucial test. Models involving the accretion of comets, asteroids or planetesimals onto neutron stars (Harwit and Salpeter 1973; Shklovskii 1974; Newman and Cox 1980; Howard, Wilson and Barton 1981; Colgate and Petschek 1981; Van Buren 1981; Joss and Rappaport 1984; Tremaine and Żytkow 1986; Katz 1986; Livio and Taam 1987; Pineault and Poisson 1989; Pineault 1990; Colgate and Leonard 1994) are capable of explaining the energetics of SGR if they are at distances ~ 100 pc (as classical GRB were long thought to be) but do not release enough energy to explain them at the required distances across the Galaxy or in the LMC, at which energies $\sim 10^{41}$ erg are

required ($\sim 4 \times 10^{44}$ erg for March 5, 1979; Cline 1980).

Models involving processes resembling scaled-up Solar flares (Stecker and Frost 1973; Katz 1982; Liang and Antiochos 1984; Melia and Fatuzzo 1991; Katz 1993, 1994) have been popular because both flares and GRB have irregular spiky time structure, while both flares and SGR repeat at irregular intervals. The energy of neutron star magnetospheres with $B < 10^{13}$ gauss is sufficient to explain all SGR phenomena except the superburst of March 5, 1979 (where a deficiency $O(10)$ might optimistically be attributed to anisotropic emission, a larger field, or to regeneration by an interior rotational dynamo). However, models of this type are unable to explain any of the temporal or spectral properties of SGR, their rarity, or their association with young supernova remnants, and must attribute them to the mysterious properties of flares, whether on the Sun, other stars, or neutron stars. It is also difficult to see how to produce a flare in a magnetosphere (where current paths are open and force-free) or within a neutron star (where the conductivity and density are extremely high, and any energy dissipated is thermalized and diffuses slowly); see Carrigan and Katz (1992). Further, models involving magnetic flares or internal rotational relaxation might be expected to be associated with pulsar glitches (Pacini and Ruderman 1974; Tsygan 1975), but no such association has ever been observed.

An important clue is the rarity of SGR. Kouveliotou, *et al.* (1994) established that there are < 7 (and possibly only the known 3) SGR presently active in our Galaxy, implying that either the SGR phase is only $\leq 10\%$ of the first 10^4 years of a neutron star's life (studies of the SNR in which SGR are embedded imply that the neutron stars which produce SGR are no more than $\sim 10^4$ years old) or that only $\leq 10\%$ of neutron stars ever become SGR. There is something special about these neutron stars.

The model we suggest depends on the discovery (Wolszczan and Frail 1992) of two planets orbiting PSR 1257+12. Although this is a fast, low-field and probably old (characteristic age 8×10^8 years) pulsar, we draw an analogy with the young, slow (8 sec in SGR 0526-66) and probably high-field (to produce the rotational modulation of March 5,

1979) neutron stars associated with SGR. The planets of PSR 1257+12 have been argued to be the residue of the evaporation of a companion star, but it is unclear how to form planets at a distance of ≈ 0.5 AU from an evaporating companion whose orbital radius (inferred from binary pulsars presently observed to be evaporating their companions) is $\sim 10^{-2}$ AU. Instead, we suggest that the planets of PSR 1257+12 existed before and survived its formation, and that similar surviving planets are the key to understanding SGR.

If planets survive a supernova which produces a neutron star, they will be left in eccentric orbits as a result of loss of stellar mass and of ablation. The longitudes of periastron of these orbits depend on the planets' longitudes at the time of the supernova, and will be uncorrelated. If the orbits are coplanar, the eccentricities are substantial (as observed for some binary pulsars, whose eccentricities are similarly produced by supernova mass loss) and the initial semi-major axes were comparable (as observed for terrestrial planets in the Solar system, and for the planets of PSR 1257+12) then there is a substantial probability the orbits will intersect and the planets will collide.

Both colliding planets have the same sense of angular momentum, but the angular momentum of individual mass elements is not conserved in the collision (its integral is conserved, of course), so that some of the collision debris may have zero or very small angular momentum. These fragments will quickly fall onto the neutron star. Fragments with somewhat larger angular momentum may later lose it, producing an accretional rain extending over a lengthy period as they are depleted. A history qualitatively resembling that of SGR 0526-66 is suggested, with a single superburst followed by a long period of occasional smaller bursts. If this is correct (it is not required by the rest of the model) SGR 1806-20 and SGR 1900+14 had superbursts which preceded the development of gamma-ray astronomy.

In §2 we discuss the survival of planets orbiting a supernova. §3 contains an estimate of the rate of planetary collisions. The problem of angular momentum distribution and

evolution of debris is briefly discussed in §4. Expected and observed radiation properties are compared in §5. All of these discussions are preliminary and rough; more careful calculation will be justified only if the model survives preliminary scrutiny. §6 contains a brief summary discussion.

2. Planetary Survival

Planets must first survive the pre-supernova star. Consider a planet of mass $M_p = 3M_E$ (M_E is the Earth's mass), the minimum mass permitted for the planets of PSR 1257+12, and iron composition, in circular orbit of radius $R = 0.5$ AU (again resembling PSR 1257+12, although the pre-supernova orbit may be somewhat smaller than a circularized post-supernova orbit). More massive or more distant planets will be more robust, but the assumed parameters are sufficient to make survival likely. It is probably necessary that the planet avoid engulfment by the pre-supernova star, which would lead both to evaporation in the interior radiation field and to a rapid inward death spiral resulting from hydrodynamic drag. The radii of pre-supernova stars are controversial, and it is possible that engulfment may be avoided with $R = 0.5$ AU; alternatively, it is not unlikely that some pre-supernovae will be accompanied by planets (less readily detectable by pulsar timing studies) with orbits large enough to avoid engulfment even by a red giant; the existence of the major planets in the Solar system is evidence for the existence of such planets.

The surface effective temperature T_e of a planet, averaged over its surface, is

$$T_e = \left(\frac{L\epsilon_a}{16\pi R^2 \epsilon_e \sigma_{SB}} \right)^{1/4} \approx 5000^\circ \text{ K}, \quad (1)$$

where L is the stellar luminosity, ϵ_a its mean absorptivity, ϵ_e its mean emissivity, and σ_{SB} the Stefan-Boltzmann constant; we have taken $\epsilon_a = \epsilon_e$ and $L = 10^{38}$ erg/sec, appropriate to a luminous pre-supernova star. The thermal energy should be compared to the surface binding energy of an iron atom of mass m_{Fe} :

$$\frac{k_B T_e a}{GM_p m_{\text{Fe}}} \approx 0.005, \quad (2)$$

where we have taken the planetary radius $a = 8 \times 10^8$ cm, the radius of a zero-temperature iron planet of $3M_E$ (Zapolsky and Salpeter 1969). If the iron atmosphere is, on average, singly ionized, as appropriate at T_e , its molecular weight is $m_{\text{Fe}}/2$ and the value in Eq. (2) should be doubled. The Boltzmann factor for thermal evaporation is then $\sim \exp(-100) \sim 10^{-43}$, and the rate of evaporation is negligible.

The thermal diffusivity of hot iron (using data for solid iron near its melting temperature) is ~ 0.1 cm²/sec. In the $\sim 10^6$ year lifetime of a bright pre-supernova star the surface heat diffuses only $\sim 2 \times 10^6$ cm into the interior; most of the interior remains cool and solid. In any case, the estimated T_e would not make a large change in the equation of state at the characteristic pressure $P_p \sim GM_p^2/a^4 \sim 5 \times 10^{13}$ erg/cm³. As a result, the zero-temperature value of a remains a good approximation.

The next threat to a planet is the supernova itself. The near-circular orbits observed for PSR 1257+12 may perhaps be explained by a quiet collapse without mass loss other than neutrino radiation, but our SGR model requires substantial eccentricity and mass loss. We consider a low energy supernova resembling the Crab supernova, whose debris shell has mass $\Delta M = 0.2M_\odot$ and velocity $v_{SN} = 2 \times 10^8$ cm/sec, and a high energy supernova with $\Delta M = M_\odot$ and $v_{SN} = 10^9$ cm/sec. The impulse delivered by the momentum in the debris shell corresponds to an impulsive velocity change of the planet

$$\Delta v \approx \frac{\Delta M v_{SN} a^2}{4R^2 M_p} \approx 3 \frac{\Delta M}{M_\odot} \frac{v_{SN}}{10^9 \text{ cm/sec}} \text{ km/sec}, \quad (3)$$

Even for the energetic supernova the delivered impulse is sufficient only to induce an eccentricity < 0.1 , and insufficient to contribute significantly to disruption of the planetary orbit.

The intercepted kinetic energy KE is more important, and its ratio to the planet's characteristic binding energy $E_{bind} \sim GM_p^2/a$ is

$$\frac{KE}{E_{bind}} \sim \frac{\Delta M v_{SN}^2 a^3}{8R^2 GM_p} \sim 100 \frac{\Delta M}{M_\odot} \left(\frac{v_{SN}}{10^9 \text{ cm/sec}} \right)^2, \quad (4)$$

For a Crab-like supernova the intercepted kinetic energy is insufficient to disrupt the planet, and a numerical hydrodynamic calculation would probably show that most of it is concentrated in surface blowoff and radiation, leaving the planet's dense core unscathed. However, the more energetic supernova would imply $KE \sim 100E_{bind}$ and requires more careful attention.

In fact, a supernova debris shell is spread by adiabatic expansion into a wind whose thickness ΔR is $\sim 0.3R$ at a distance R . Its stagnation pressure P_{SN} is

$$P_{SN} \sim \frac{\Delta M v_{SN}^2}{8\pi R^2 \Delta R} \sim 10^{12} \frac{\Delta M}{M_{\odot}} \left(\frac{v_{SN}}{10^9 \text{ cm/sec}} \right)^2 \text{ erg/cm}^3. \quad (5)$$

Even for the energetic supernova, $P_{SN} \ll P_p$, so that the pressure of impacting debris is insufficient to disrupt the planet, although there will be some (difficult to calculate, even numerically) mass loss by ablation and surface entrainment. The kinetic energy of the supernova wind flows around the planet, guided by the stagnation pressure at the planetary surface. It is not coupled into the planetary interior and does not disrupt the planet. A useful (though inexact) hydrodynamic analogy is a spacecraft re-entering the Earth's atmosphere, whose kinetic energy far exceeds its heat of vaporization, but which suffers very little ablation.

Ablation will produce a recoil which depends on the amount of energy hydrodynamically coupled to the planetary interior. This is also difficult to calculate. Because the ablation pressure is small (even for energetic supernovae) and the density mismatch is large between the wind, which has density $\sim \Delta M/(4\pi R^2 \Delta R) \sim 10^{-6} \text{ gm/cm}^3$ and the planet ($\sim 10 \text{ gm/cm}^3$), this coupling is likely to be poor, and the resulting velocity of planetary recoil will be of order that given by Eq. (3).

It thus appears that a planet with the assumed parameters would survive the pre-supernova star and a Crab-like supernova essentially intact, and would probably also survive even the most energetic supernovae. Its orbit is, however, affected by the loss of mass in the supernova explosion, according to the classic theory of Blaauw (1961). If less than

half the pre-supernova's mass is lost in a symmetric (recoiless) explosion then the planet will remain bound, but in an eccentric orbit.

Recoil by the newly formed neutron star would, itself, unbind the planet if the recoil velocity exceeded the planetary orbital velocity (about 50 km/sec for the assumed parameters). Most pulsars have velocities substantially exceeding this value. However, there is evidence (Katz 1975) from the presence of neutron stars in globular clusters for their production with recoil velocities less than the cluster escape velocities, which are typically ~ 20 km/sec.

Kulkarni, *et al.* (1994) and Rothschild, Kulkarni and Lingenfelter (1994) have argued that the neutron stars producing SGR 1806-20 and SGR 0526-66 are offset from the centers of their supernova remnants by amounts corresponding to space velocities of 500 km/sec and 1200 km/sec, respectively, inconsistent with the hypothesis of this paper. The brightness distributions of these remnants are rather irregular; if the observed shapes of the remnants are attributed to the collision of supernova debris with asymmetrically located interstellar clouds then it may be that the SGR are actually in the dynamical (rather than the X-ray or radio) centers of their supernova remnants, reconciling these observations with the low recoil velocities required by our hypothesis.

The planets orbiting PSR 1257+12 have small eccentricities ($e \approx 0.02$). Thus, while they may be taken as evidence for the survival of planets (though post-supernova formation has been considered), they could be considered arguments against significant eccentricity of the planetary orbits. However, the characteristic (spin-down) age of PSR 1257+12 is 8×10^8 years, and its actual age could be of this order, affording ample time for weak dissipative processes (such as interaction with the pulsar's radiation or a residual disk) to circularize the planetary orbits. In addition, PSR 1257+12 has a spin period of 6 ms and a correspondingly intense radiation field, in contrast to the 8 sec period inferred for SGR 0526-66, so these systems may differ in many aspects of their history and properties.

3. Planetary Collision Rate

We assume intersecting coplanar eccentric planetary orbits with semi-major axes $R \approx 10^{13}$ cm. The orbital velocities (≈ 50 km/sec) exceed the escape velocities from the planets (≈ 20 km/sec) so that their collision cross-sections are essentially geometrical. In each orbit of circumference $\approx 2\pi R$ the length which corresponds to a planetary collision is $8a$, allowing for two intersections (any approach of the planetary centers to within a separation of $2a$ in any direction leads to collision) and ignoring the fact that the angle between the orbits at intersection is likely to be substantially less than $\pi/2$. The probability of collision per orbit is $\approx 8a/(2\pi R)$, and the characteristic time to collision t_c is

$$t_c \approx P \frac{2\pi R}{8a} \approx 4000 \text{ years}, \quad (6)$$

where we have taken the synodic period of one planet with respect to the other $P \approx 0.5$ year, following PSR 1257+12. This value of t_c is consistent with the observational inference that SGR occur in supernova remnants which are no more than 10^4 years old.

The assumption of coplanar orbits is essential to Eq. (6); the relative inclination angle i must not greatly exceed $2a/R \sim 2 \times 10^{-4}$ rad. This is substantially smaller than inclinations found in our Solar system, in which relative inclinations are $\sim 1^\circ$ or more. However, the pre-supernova star is very extended, and planets will have strong tidal interactions with it, and through it with each other. It is therefore not implausible that their orbits will relax to accurate coplanarity. The closest Solar system analogs, the satellite systems of the major planets, although closer to coplanarity than the Solar system itself, are not directly applicable because the major planets have large equatorial bulges (not expected for a giant star) and their satellites are also perturbed out of their orbital planes by other planets and the Sun.

If the orbits are not coplanar, with $i \gg 2a/R$, the planets will not collide unless there is a fortuitous coincidence of a node with one of the longitudes of equal radii. Differential precession and apsidal motion may produce approximate intersection and collision, but t_c

is increased by a factor $O(R \sin i/2a)$ if the motion is ergodic; there is also the possibility of a stable non-colliding state such as that between Neptune and Pluto.

4. Collision Debris

Two colliding planets will both have the same sense of angular momentum. How may they then produce debris in orbits of essentially zero angular momentum, as required for accretion onto the neutron star? In a collision there will be large internal forces which will redistribute momentum and angular momentum over the colliding planets. Materials strength and gravitational binding are small compared to the typical collisional stresses of $\sim 10^{14}$ erg/cm³ for planets whose orbital velocities are about 50 km/sec, so much or all of the planets (depending on impact parameter) will be disrupted into a spray of fragments of various sizes. The specific angular momentum distribution is unknown, so we will assume it to be uniform from $-0.5L_0$ to $2.5L_0$, where L_0 is the mean initial specific angular momentum. The results depend on the value of the distribution at $L \approx 0$ (it is essential that it be nonzero there) but not on its shape; the assumption of some debris with $L < 0$ is relevant to subsequent debris-debris collisions.

The accretion of an asteroid by a magnetic neutron star was discussed by Colgate and Petschek (1981); similar processes occur here, but the greater mass of the accreting object makes the magnetic field less important in the dynamics. Debris with low angular momentum moves in essentially parabolic orbits, with periastron distance $h = L^2/(2GM)$. A neutron star magnetic moment μ will stop an iron fragment of $s = 3 \times 10^6$ cm radius (required to explain a typical SGR burst of 10^{41} erg) at a periastron distance

$$h_s < \left(\frac{\mu^2}{8\pi GM \rho s} \right)^{1/4} \approx 1.7 \times 10^6 \left(\frac{\mu}{10^{30} \text{ gauss cm}^3} \right)^{1/2} \left(\frac{8 \text{ gm/cm}^3}{\rho} \right)^{1/4} \text{ cm.} \quad (7)$$

This will not exceed the neutron star's radius in order of magnitude. Compression of the infalling matter by the neutron star's gravitational field only strengthens this conclusion.

The limit on L for accretion by direct infall from the collision site is approximately

that required for ballistic impact with the surface of a neutron star of radius r :

$$L < (2GMr)^{1/2} \approx 2 \times 10^{16} \text{ cm}^2/\text{sec}. \quad (8)$$

For orbits like those of the planets of PSR 1257+12 $L_0 \approx 4 \times 10^{19} \text{ cm}^2/\text{sec}$. The total mass available for prompt infall is

$$M_{sb} \sim 2M_p \frac{L}{3L_0} \sim 6 \times 10^{24} \text{ gm}. \quad (9)$$

The gravitational energy released when this mass accretes is $\sim 6 \times 10^{44} \text{ erg}$, approximately that required (Cline 1980) to explain the superburst of March 5, 1979.

This prompt accretion occurs roughly 0.2 of an orbital period following the collision, or some weeks later. In order to explain the observed superburst of March 4, 1979, which had a very intense sub-burst lasting ~ 0.1 second followed by most of its energy over a period of several minutes, the initial accretion must have been of a single solid body of $\sim 10^{25} \text{ gm}$, rather than an extended cloud of small particles or fluid. This is not impossible; the planetary interiors are expected to be solid metal (§2).

Subsequent repeating bursts require the accretion of smaller bodies, typically $\sim 10^{21} \text{ gm}$ but with wide dispersion. A few of these may have left the collision with L small enough to collide with the neutron star's surface, but with more outward-directed velocity than the fragment accreted first, so their accretion follows the superburst by weeks to months. To explain repetitions at longer times requires fragments born with greater L which they lose over a longer period. A number of mechanisms are possible, including angular momentum loss to the magnetosphere in non-impacting periastron passages (Van Buren 1981), and subsequent collisions between debris or between debris and surviving planetary cores (possibly including other planets not involved in the collision).

Most of these processes are difficult to calculate. The resulting temporal distribution of bursts depends on the detailed angular momentum distribution of the collision debris, which is also unknown. Stochastic gravitational perturbation of debris by planets may be

estimated, and amounts to $\sim 2 \times 10^{14}$ cm²/sec per orbit. This suggests that in $\sim 10^4$ orbits (several thousand years) the total amount accreted might be comparable to that in the initial superburst, roughly consistent with observation.

The tidal breakup radius of an iron fragment of radius $s = 3 \times 10^6$ cm ($\sim 10^{21}$ gm) and strength $Y \sim 10^{10}$ erg/cm³ is $r_t \sim (GM\rho s^2/2Y)^{1/3} \sim 10^{10}$ cm (the nominal Roche limit is several times larger, but irrelevant in the presence of this material strength), which poses a problem for all gradual orbital evolution processes—the fragment will be disrupted before it loses enough angular momentum to be accreted. Disruption produces a mix of smaller fragments and perhaps fluid, which may accrete steadily through a disk (if not blown away by the pulsar wind), leading to a steady X-ray source of low luminosity. Debris-debris collisions or rare close encounters with planets may resolve this problem by impulsively transferring fragments with $L > (2GMr_t)^{1/2}$ into collision orbits with the neutron star, without requiring them to survive diffusion through values of angular momentum at which they would be disrupted without accretion.

5. Radiation

The observed spectra of SGR are typically fitted to optically thin bremsstrahlung spectra with $k_B T \approx 40$ KeV, but may perhaps also be fitted to black bodies with $k_B T \approx 10$ – 20 KeV. Such a black body with a neutron star's surface as its radiating area is consistent with the luminosities $\sim 10^{41}$ erg/sec typically observed, as may be the much harder spectrum observed during the more luminous initial 0.1 second of the March 5, 1979 superburst.

The most striking fact about these luminosities, as pointed out by Cline (1980) for SGR 0526-66 and by Atteia, *et al.* (1987) and Kouveliotou, *et al.* (1994) for the other SGR, is that they are apparently super-Eddington by several orders of magnitude. Two explanations are possible. One is that they are not really super-Eddington, because the neutron stars' magnetic fields are sufficiently large that the opacity at the observed frequencies is far below that of free electron scattering for radiation propagating with its

electric vector perpendicular to \vec{B} . This open spectral/polarization “window” dominates the Rosseland mean opacity, and increases the Eddington limit above its nominal (unmagnetized electron scattering) value. This hypothesis requires magnetic fields in excess of 10^{13} gauss, and predicts strong linear polarization of the emergent radiation.

In the second explanation the luminosity is genuinely super-Eddington, but the radiation pressure is contained by the magnetic stress (Katz 1982), rather than the weight of overlying matter. In this case the radiation energy which may be contained is limited to approximately the magnetic energy of the magnetosphere. For $B < 10^{13}$ gauss this is adequate to explain the ordinary bursts of SGR but not the superburst of March 5, 1979.

6. Discussion

We have presented a model for SGR which may explain, at least in order of magnitude, many of their properties. The model makes certain testable predictions. A SGR may (but need not, if no fragments are born satisfying Eq. [8]) begin its activity with a superburst like that of March 5, 1979; however, if such a superburst occurs it will not have been preceded by years of ordinary bursts. The radiation is predicted to be linearly polarized, with approximately a black body spectrum. The magnetic field of the neutron star probably exceeds 10^{13} gauss, in which case no 511 KeV annihilation line can be seen (Katz 1982). A SGR has negligible visible or radio-frequency emission. Following a burst, the luminosity should decay roughly $\propto t^{-3/2}$, the result for the cooling of an impulsively heated half-space of uniform thermal impedance (Katz 1982); more quantitative results require numerical calculation with realistic neutron star models.

It is possible that in the superburst of March 5, 1979 the initial intense ~ 0.1 second of emission reflected the duration of rapid accretion, while the subsequent emission resulted from the cooling of accreted matter. If so, then the duration of accretion reflects the tidal breakup of the accreting body on infall. An elementary calculation yields a duration $4s(r_\ell/2GM)^{1/2}/5$, where $r_\ell \equiv \min(r_t, r_{Roche})$; for $s = 5 \times 10^7$ cm, corresponding to the

total energy of the superburst, this is 0.4 sec, almost as short as required.

The submillisecond rise time (Cline 1980) of the March 5, 1979 superburst requires explanation. When the compressed iron of a disrupted fragment hits the neutron star it produces a splash of radiating shock-heated matter, which is ballistically distributed over the surface on the submillisecond gravitational time scale (Howard, Wilson and Barton 1981). The rise time is short because the accreting matter is condensed, rather than gaseous; the rate of release of hydrodynamic (infall) energy rises abruptly from zero just as the density of solid iron rises abruptly from vacuum. The duration of energy release is much longer, and is set by the duration of infall of the disrupted accreting fragment.

The collision of two planets releases $\sim 10^{41}$ erg, but nearly all of this energy appears in thermal and kinetic energy of debris, and is not radiated. The luminosity of the shock-heated planets themselves resembles that of a hot white dwarf ($M_V \sim 10$), which at 10 Kpc distance corresponds to $m_V \sim 25$, surely undetectable as a rare and unpredictable event preceding gamma-ray emission. The spray of debris could have a surface area larger by orders of magnitude. In the most extreme and implausibly optimistic case most of the planets could be vaporized, and their effective radiating area could be $\sim R^2$ after a time of order the orbital period. The kinetic energy, if all radiated from this area in this time, would give $M_V \sim 4$ and $m_V \sim 19$.

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